L1 Track Triggering at CMS for the HL-LHC

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WIT2014 *Workshop on Intelligent Trackers, Philadelphia, May 14-16*

Introduction

- Upgrade to High-Luminosity LHC foreseen for Long Shutdown 3 in 2023-2025
  - Peak luminosity **5×10^{34} $cm^{-2}s^{-1}$**
  - Goal to collect **3000 fb^{-1}** over 10 years
  - Benchmark pileup **<PU>=140**
    - *Very challenging environment for the LHC experiments*

- New central tracker for CMS with triggering capabilities
  - Maintain high efficiency & keep rates under control for L1 objects
  - Different ideas for L1 track finding & fitting

- One approach is **"tracklet-based" L1 tracking**
  - Algorithmic method
  - Relies on commercial FPGA technology
    - *This presentation: tracking performance & use of tracks in L1 trigger*
    - *More details in Jorge Chaves' presentation*

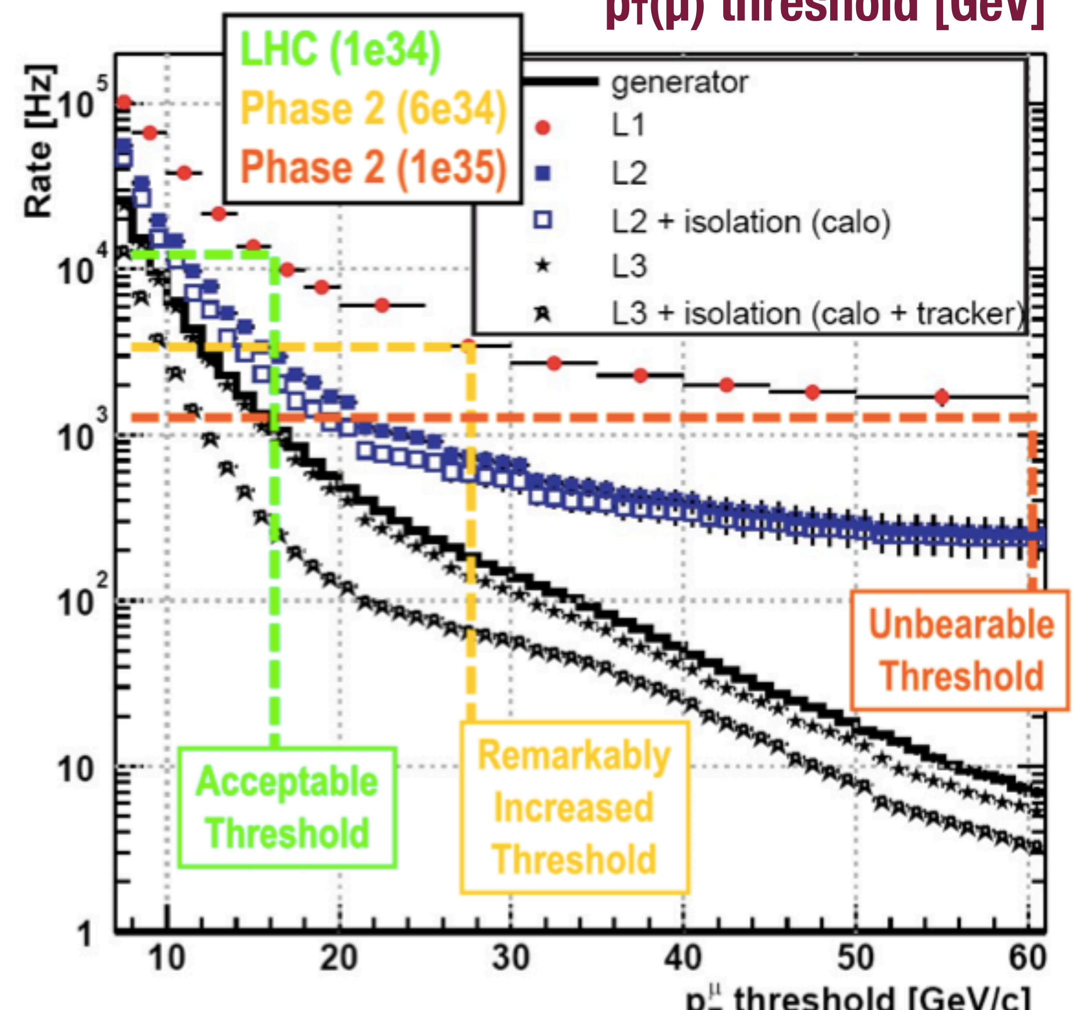
Outline

- Motivation for L1 track trigger at CMS
- Performing tracking at L1
  - Concept of track triggering
  - Tracklet-based approach to track finding
- Expected performance of tracklet-based L1 tracking from simulation
  - Tracking efficiency
  - Track parameter resolutions
- Using tracks for L1 trigger
  - Track isolation
  - e/μ identification
  - Vertexing
  - Hadronic triggers

Motivation

- With HL-LHC, μ, e & jet rates would exceed 100 kHz
  - Increasing trigger thresholds restricts physics potential (+ alone not sufficient!)
  - Key goal for CMS to maintain similar physics performance as for 2012 operation
    - *Precision measurements of Higgs properties*
    - *Sensitivity in searches for SUSY & other new physics scenarios*
  - Including tracking @ L1 significantly reduces rates

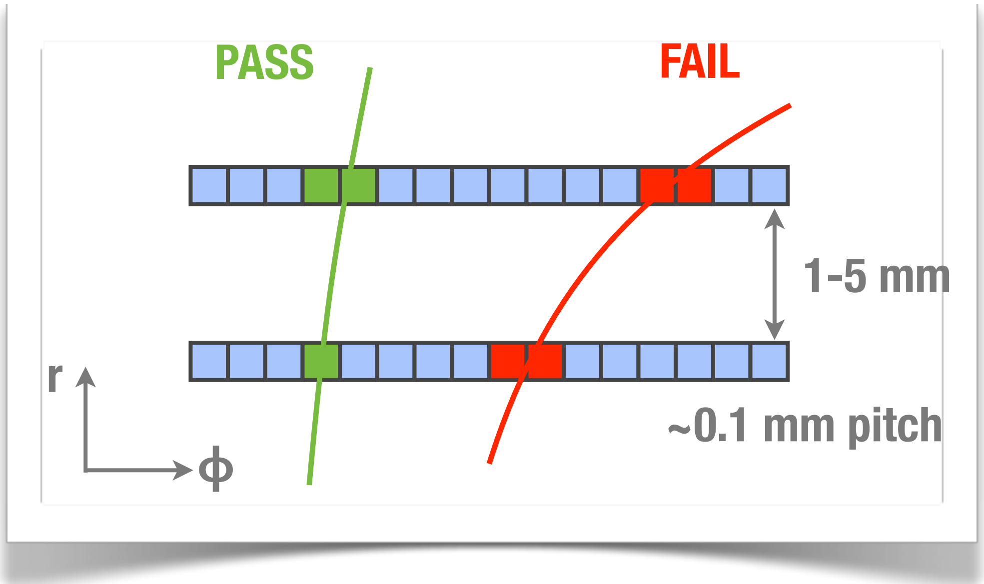
Single μ rate [Hz] vs $p_T(\mu)$ threshold [GeV]



- L1 track trigger
  - Precise momentum measurements for muons allow sharp turn-ons
  - Matching & isolation for electrons/ taus, isolation for photons
  - Vertex association for hadronic triggers

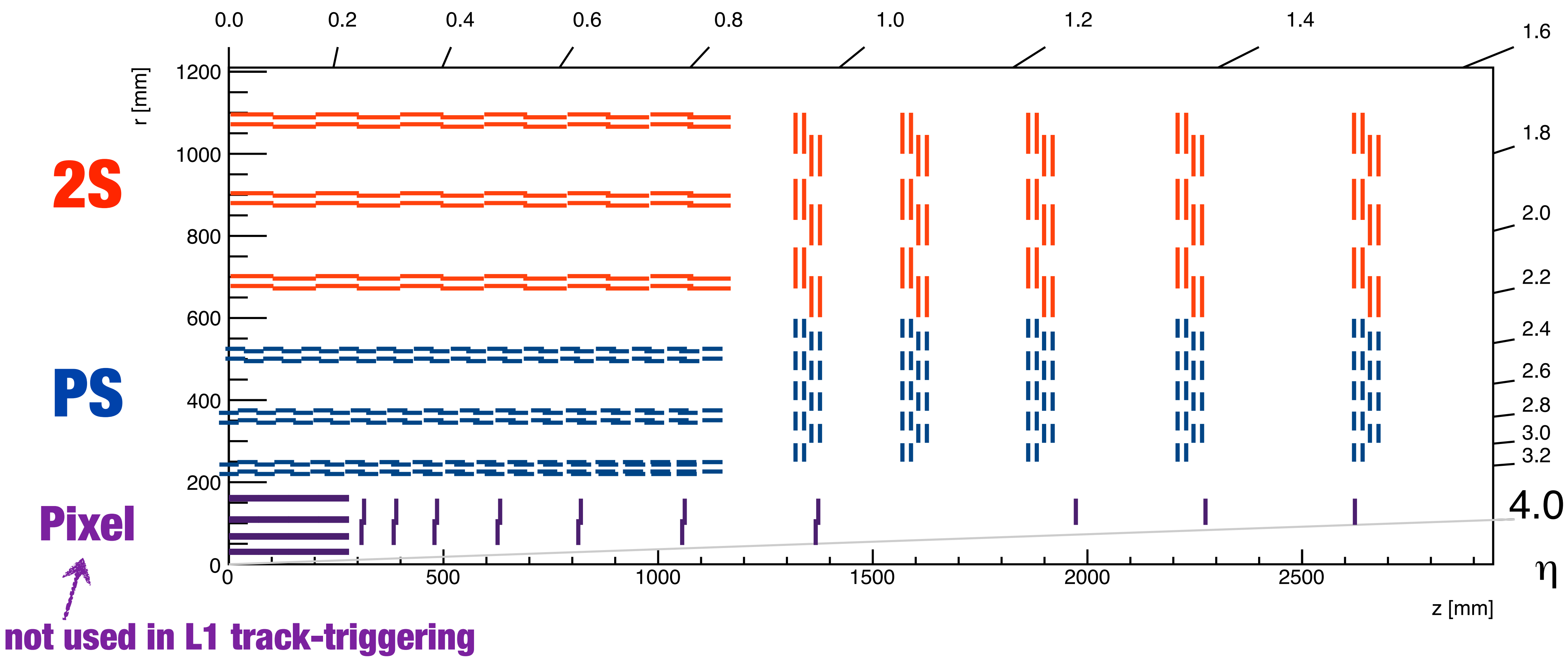
Track Trigger Concept

- Self-seeded L1 track trigger
  - Relies on local p_T reconstruction
  - Aim to reconstruct tracks with $p_T > 2$ GeV & identify z position with ~1mm precision
    - *Similar as average vertex separation at PU=140*
- "p_T modules" provide p_T discrimination through hit correlation between closely spaced sensors
  - **Stub:** Correlated pairs of clusters, consistent with 2 GeV track
- In minimum bias events, ~95% of tracks have $p_T < 2$ GeV



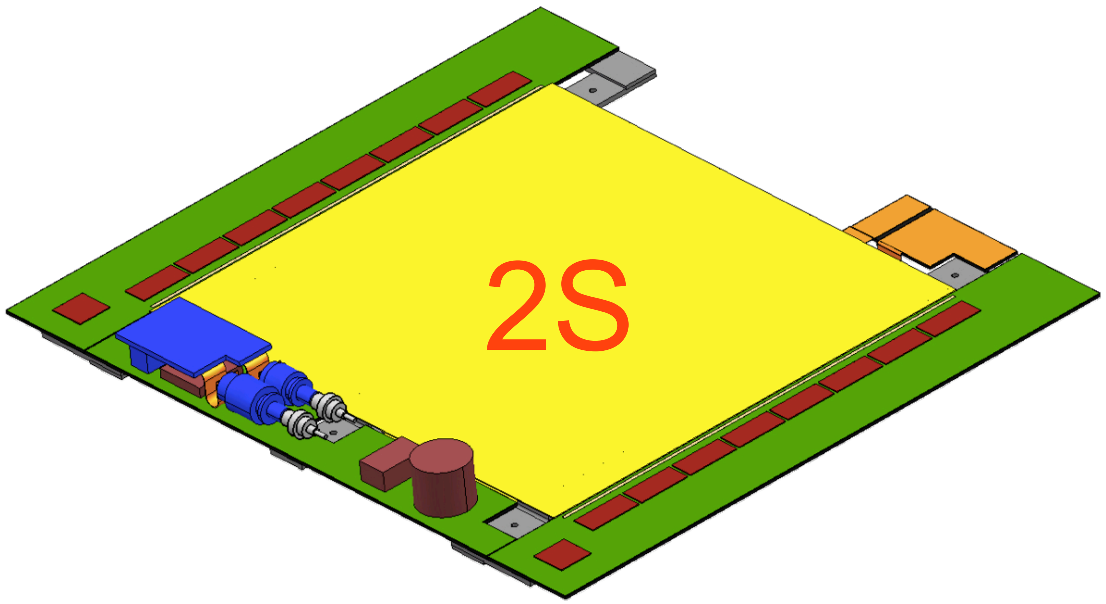
Upgraded CMS Tracker

- Baseline geometry for upgraded tracker - barrel & endcaps with 5 disks
- Two types of p_T modules
  - **2S modules** (strip-strip sensors)
  - **PS modules** (pixel-strip sensors)



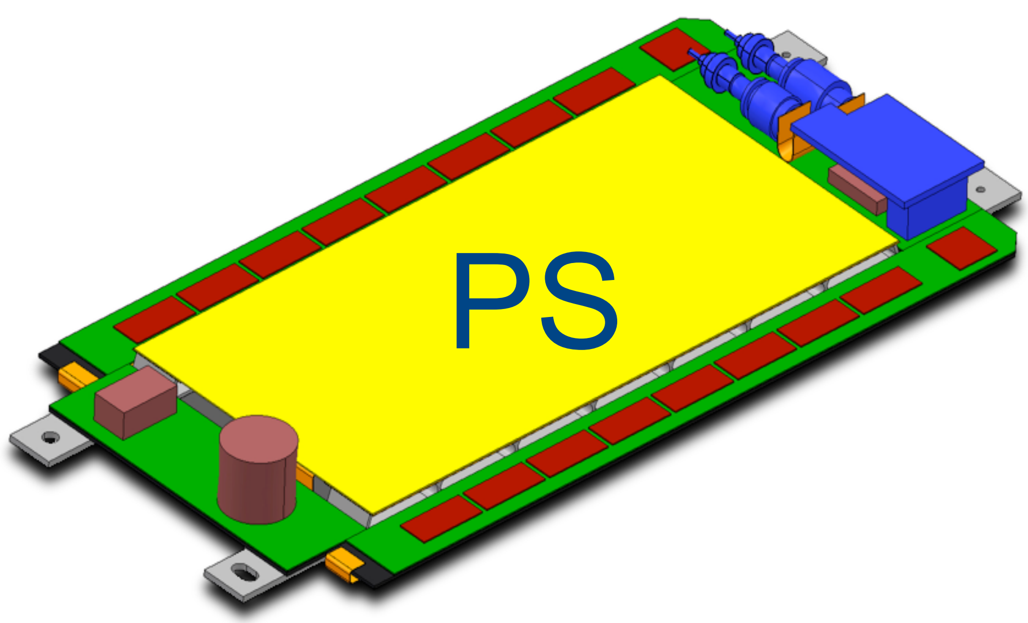
Tracker Modules

- Modules discriminate low-p_T tracks in FE electronics



2S modules

- Three outer layers of strip-strip modules
- Strip sensors 10x10 cm^2
  - *2x5 cm long strips*
  - *90 μm pitch*

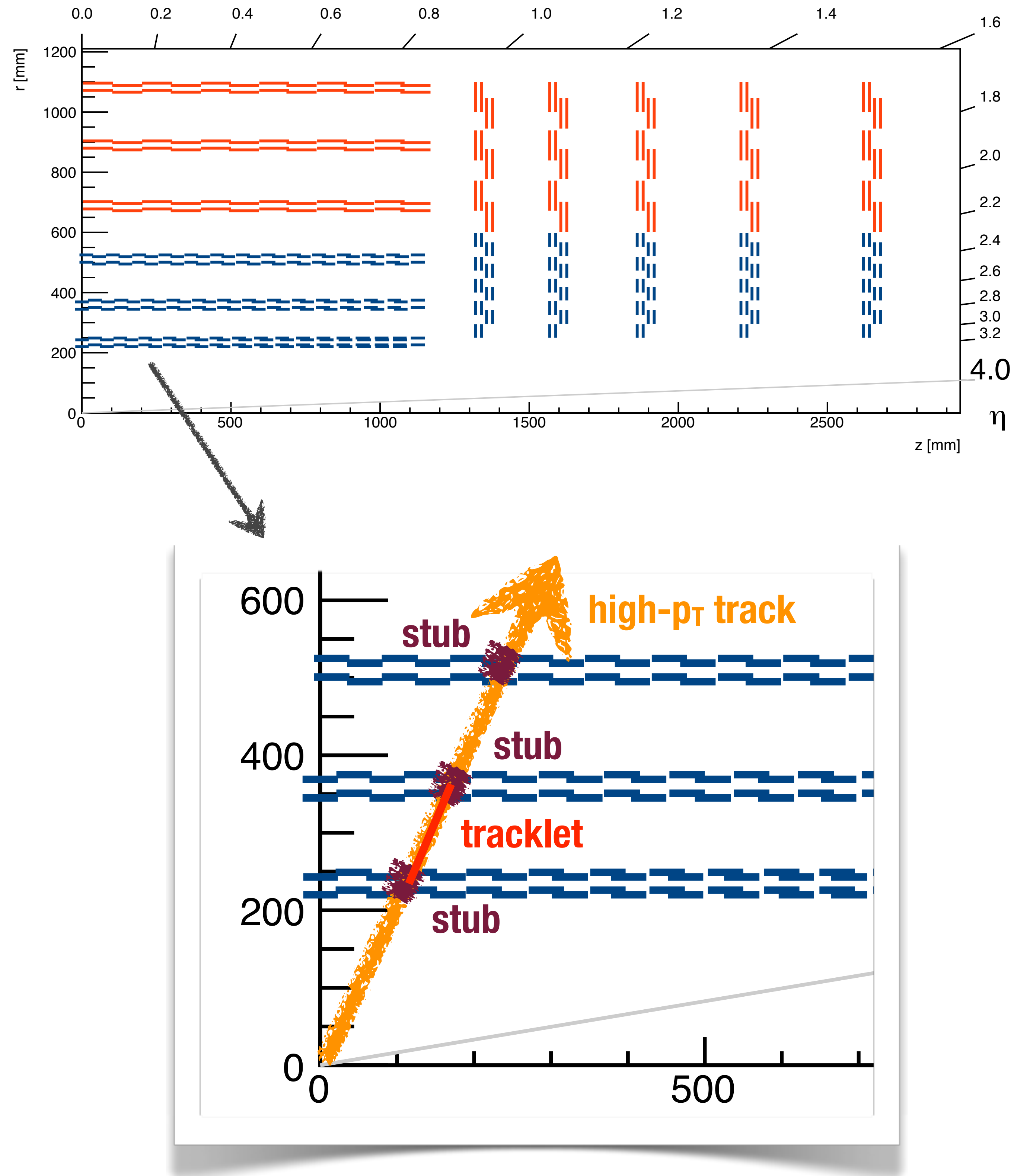


PS modules

- Three inner layers of pixel-strip modules
- Top sensor
  - *2x25 mm strips, 100 μm pitch*
- Bottom sensor
  - *1.5 mm x 100 μm pixels*

Tracklet-Based L1 Tracking

- **Seed**
  - Seed by forming tracklets from pairs of stubs in neighboring layers
    - *Rough estimate of tracklet parameters from the two stubs + constraint to beamspot*
    - *Tracklet must be consistent with $p_T > 2$ GeV, $|z_0| < 15$cm*
  - Seed multiple times
    - *L1+L2, L2+L3, L1+D1, ...*

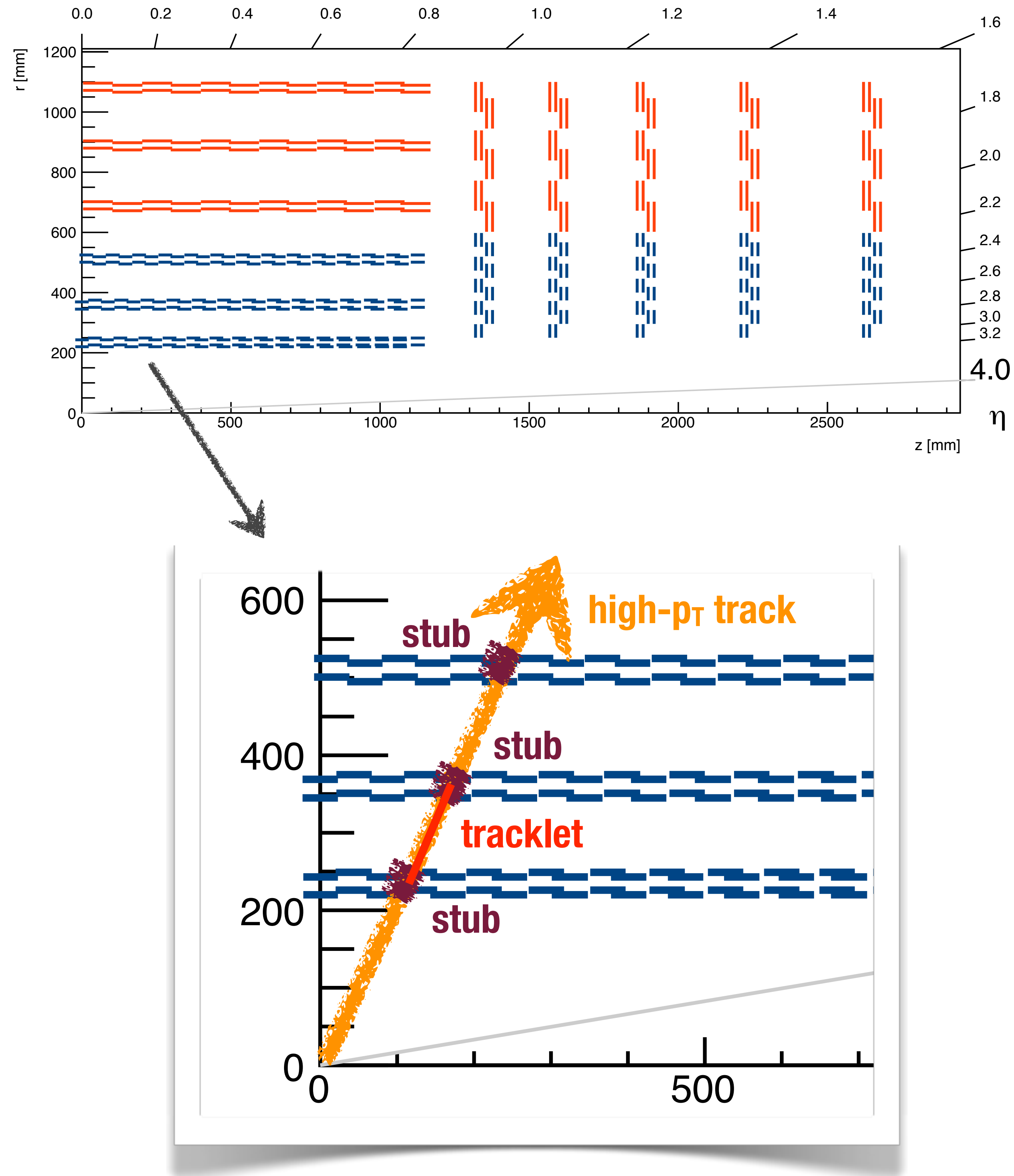


- **Project**
  - Project tracklets to other layers & disks to search for matching stubs
  - Both inside-out & outside-in

Tracklet-Based L1 Tracking

- **Fit**
  - Perform track fit of stubs matched to trajectory
    - *Linearized χ^2 fit*
  - Gives final track parameters (p_T, η, ϕ_0, z_0 & optionally d_0)

- **Duplicate removal**
  - A given track can be found many times due to seeding in multiple pairs of layers
    - *Ensures high efficiency*
  - Remove duplicates based on χ^2



Tracking Performance

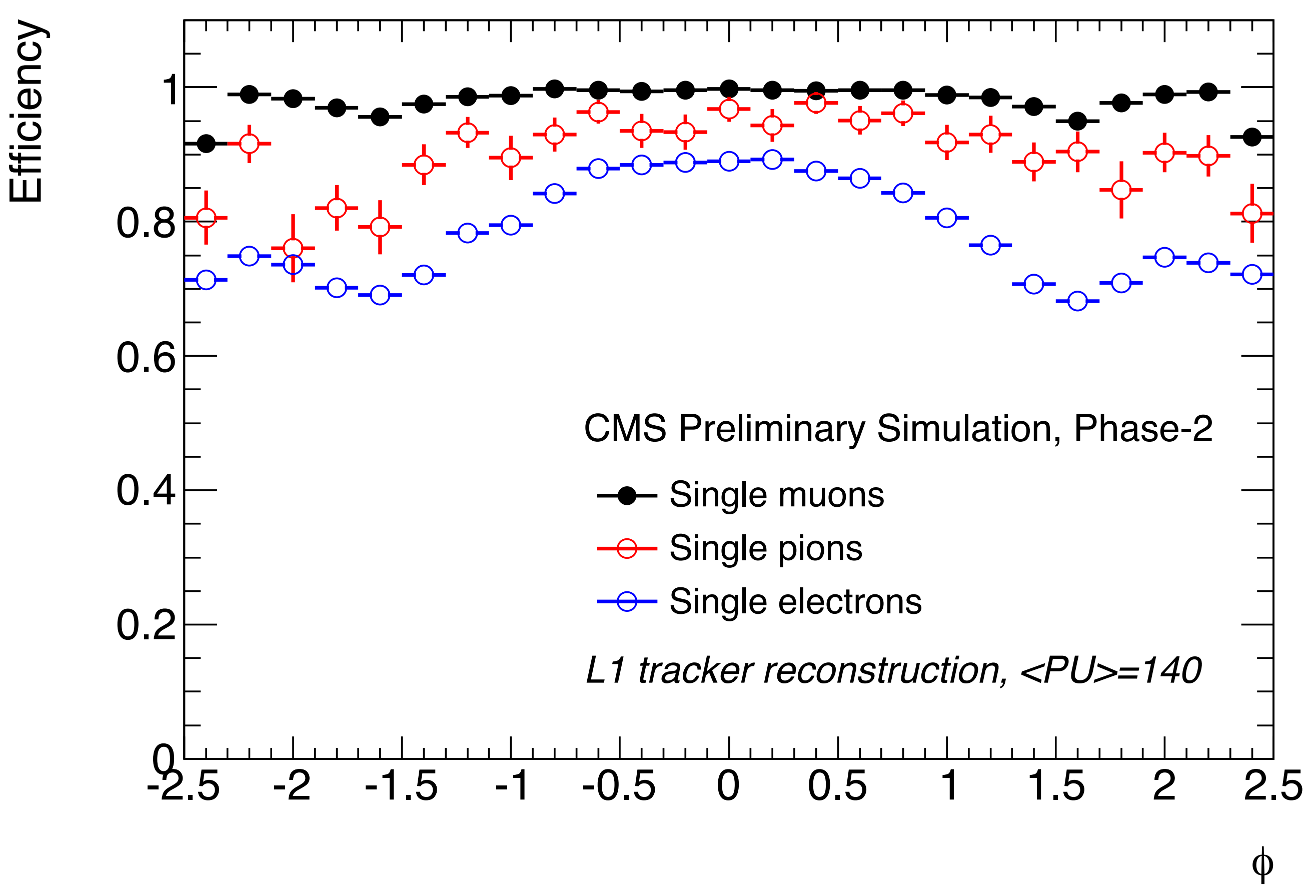
- Evaluate L1 tracking performance using simulation
- Results shown for floating-point implementation of algorithm

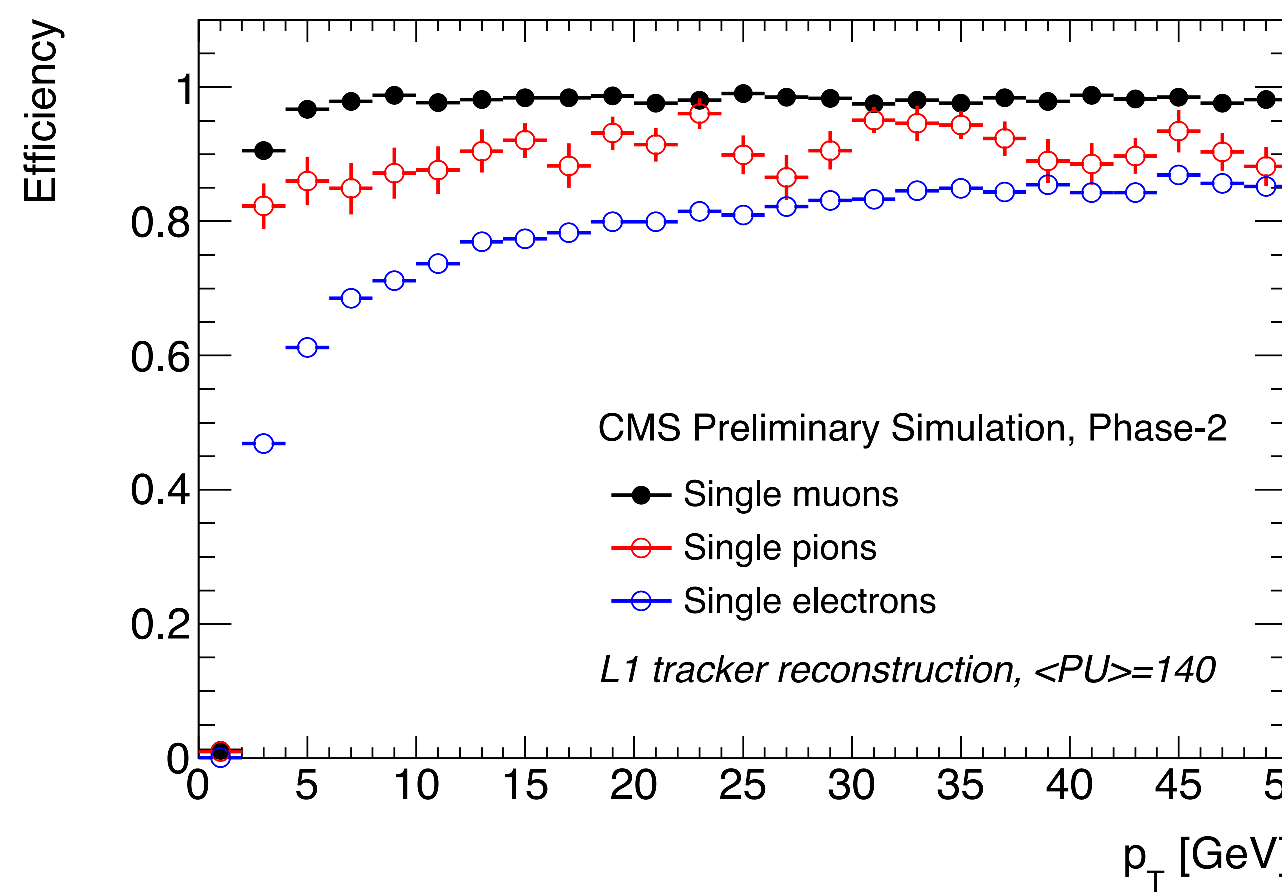
- Study performance for single-gun particles
  - Single μ, e, π of positive & negative charge
    - *Generated with flat p_T spectrum*
  - Events have <PU>=140 & bunch spacing = 25 ns @ 14 TeV
  - Efficiencies defined w.r.t. truth tracks corresponding to single-gun particle

- L1 track selection
  - **Kinematics** $p_T > 2$ GeV, $|\eta| < 2.5$
  - **Quality** $\chi^2 < 100$, track has ≥ 4 stubs

Tracking Efficiency

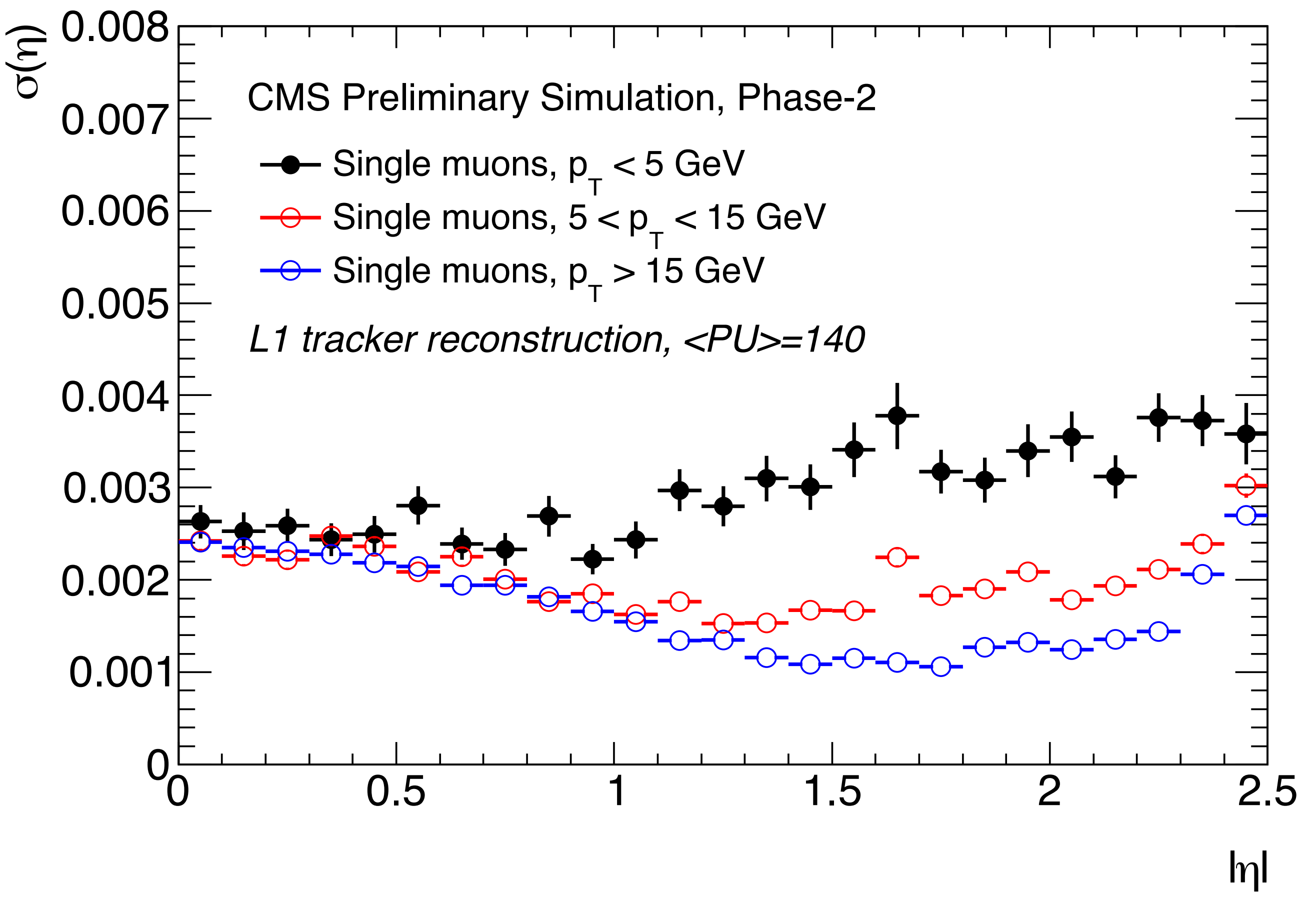
- L1 tracking efficiency as function of η & p_T for single μ, π, e with <PU>=140
  - **Muons** Sharp turn-on at 2 GeV & high efficiency across all η
  - **Pions** Somewhat lower efficiency due to higher interaction rate
  - **Electrons** Slower turn-on curve, efficiency reduced from bremsstrahlung
- For $|\eta| < 1.0$ & $p_T > 2$ GeV, efficiency for **μ**, **π**, **e** is **>99%**, **95%**, **87%**

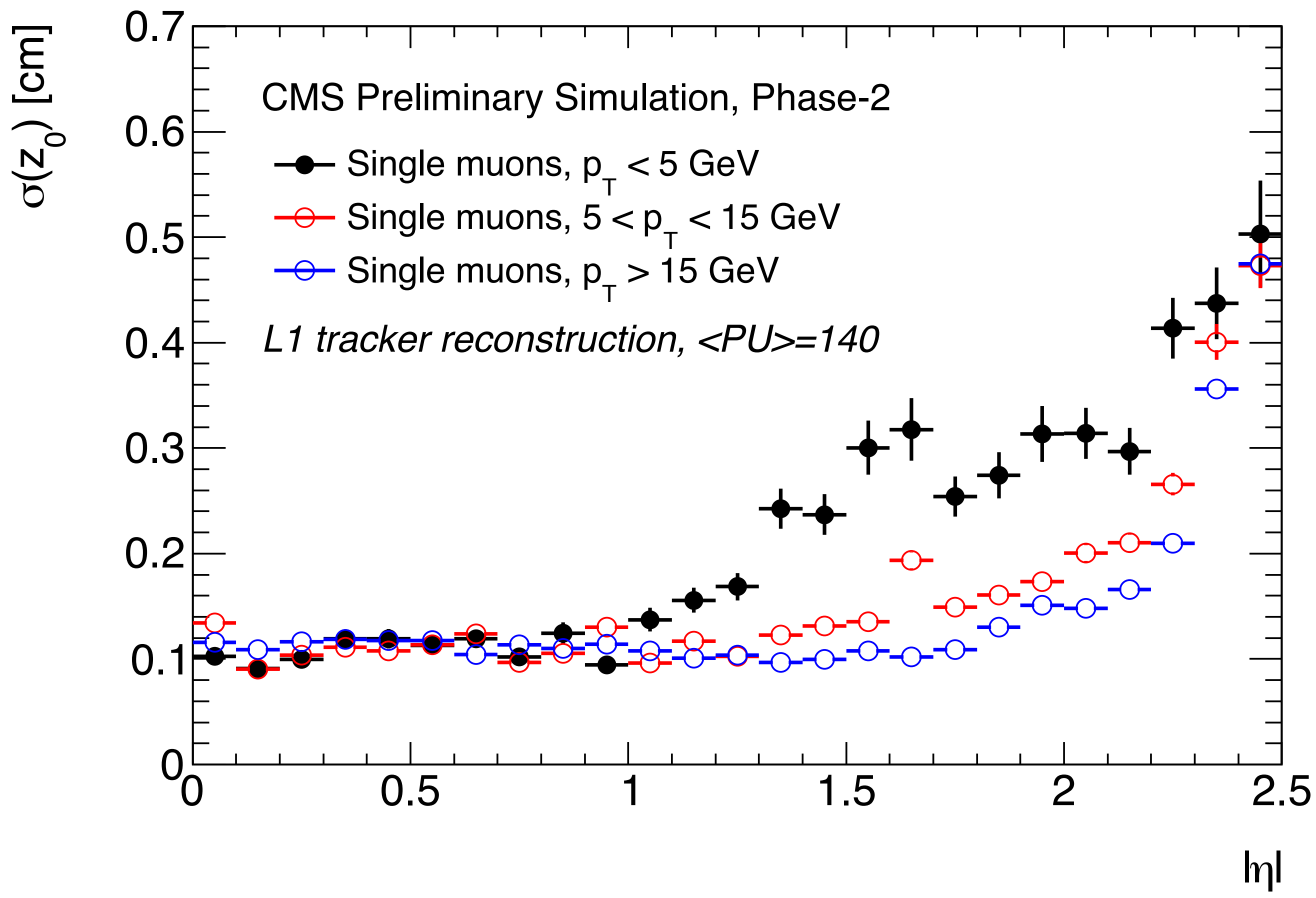




Track Resolutions

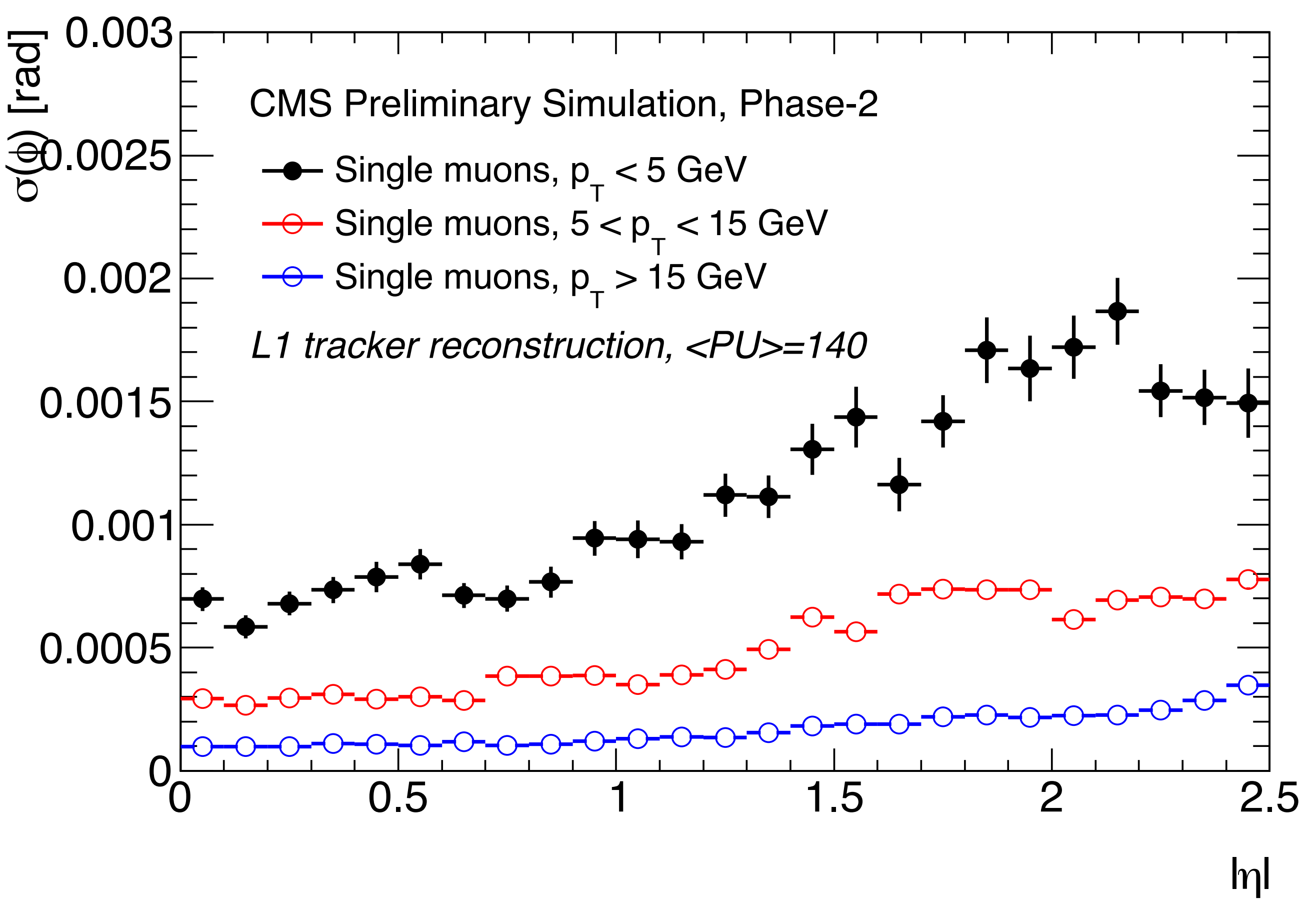
- L1 track parameter resolutions for single muons in events with <PU>=140
- Here, η & z_0 resolution vs |η| for three ranges of p_T
  - **σ(η)** ~0.002 for high p_T tracks
  - **σ(z_0)** ~1mm for a wide range of η despite large extrapolation distances thanks to PS modules

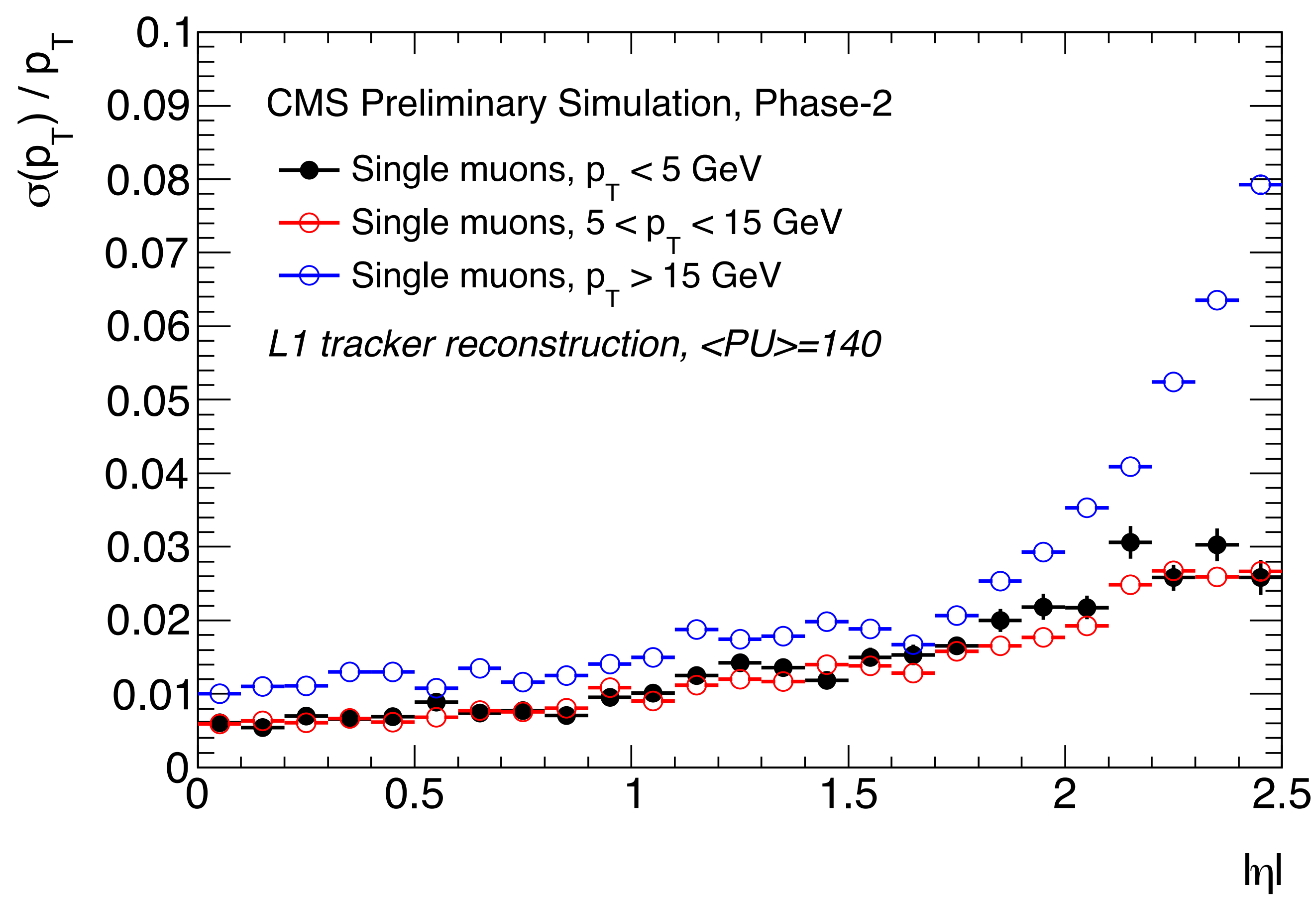




Track Resolutions

- L1 track parameter resolutions for single muons in events with <PU>=140
- Here, ϕ & p_T resolution vs $|\eta|$ for three ranges of p_T
  - **$\sigma(\phi)$** ~0.0003 for 10 GeV track at central η
  - **$\sigma(p_T)/p_T$** ~1% at central η for high-p_T track





Toward Triggers

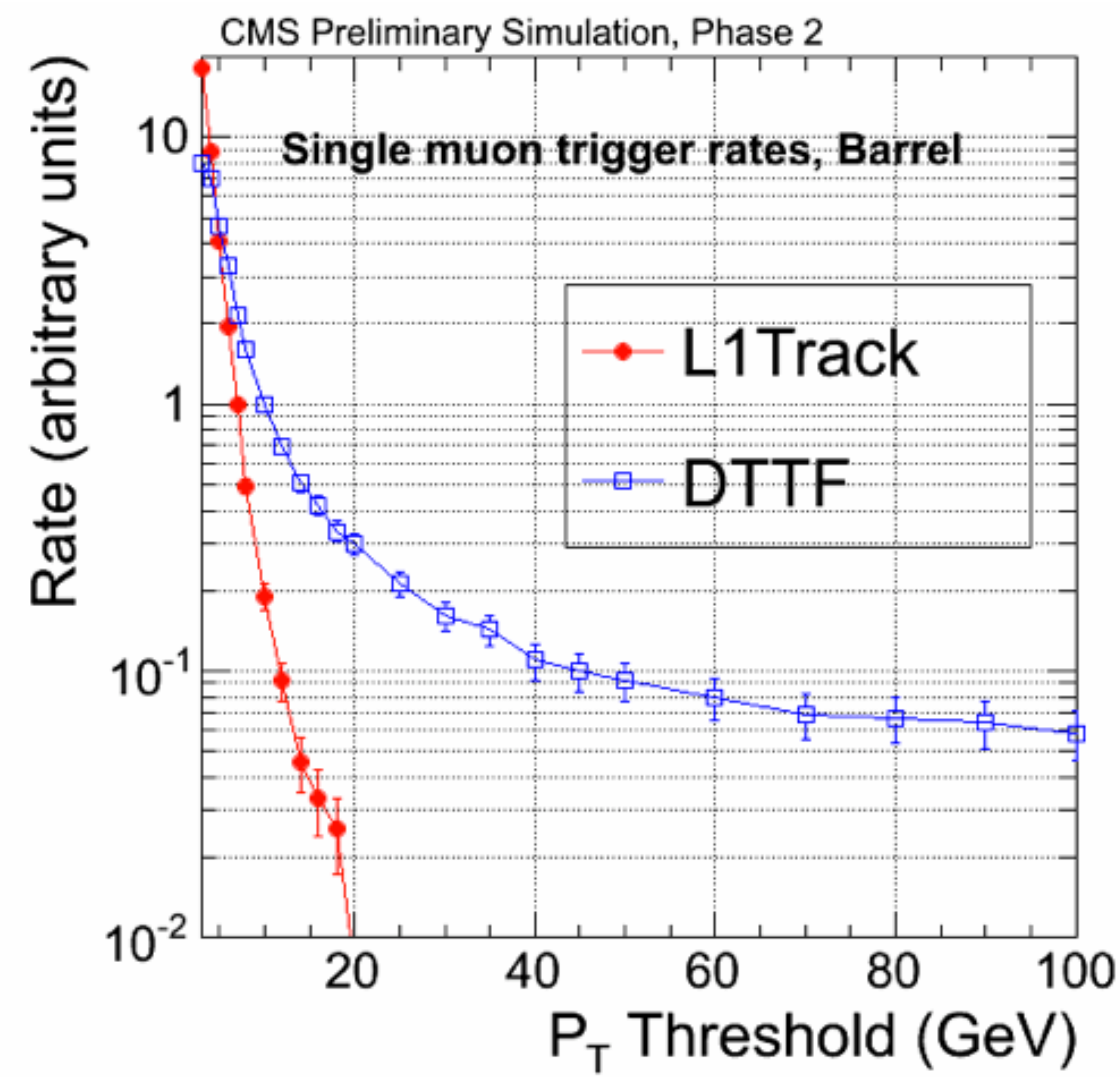
- To use the tracking, must combine L1 track information with L1 trigger objects
  - The following assumes tracks with similar performance as previous slides

- How does track trigger help reduce rates?
  - **Leptons…**
    - *Add track isolation*
    - *Improved p_T measurement*
    - *Determine z position*
  - **Photons…**
    - *Add track isolation*
  - **Hadronic…**
    - *Determine z position & require jets to originate from common vertex to reject jets from PU interactions*
    - *Multijet, H_T & missing H_T triggers*
  - **Primary vertex & track MET…**

Muons

- Rates for drift tube trigger primitives (DTTF) flattens at high thresholds
- Matching DT trigger primitives with L1 tracks gives large rate reduction

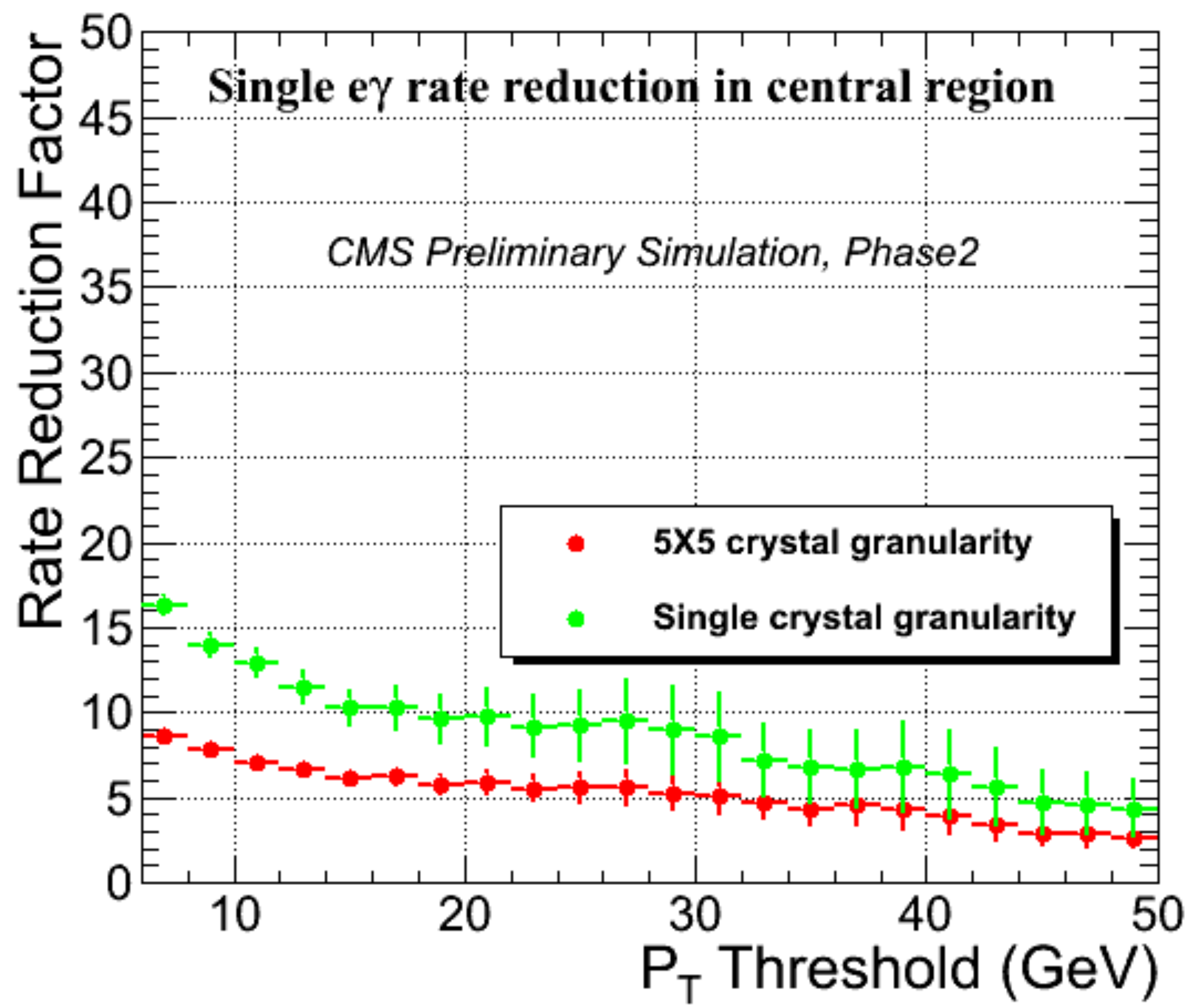
- Factor **>10** reduction for p_T thresholds above ~14 GeV
  - Not including tracker isolation
- Rates normalized to present trigger at 10 GeV



Electrons

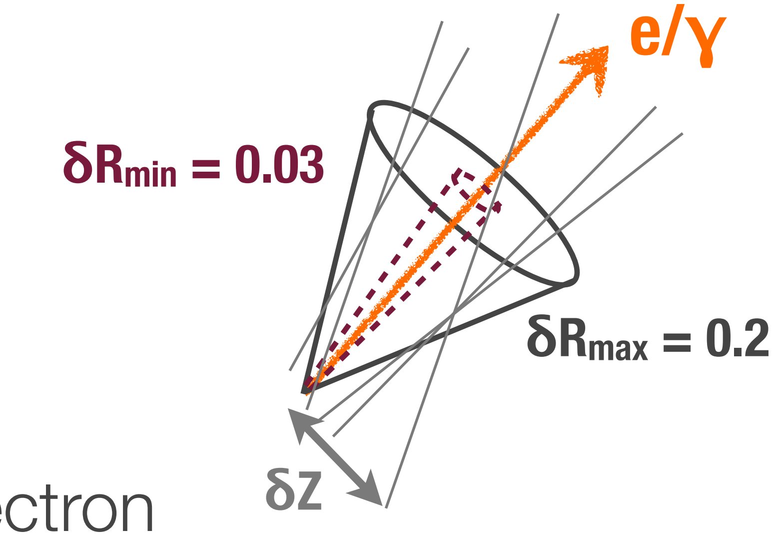
- Matching L1 e/γ objects to L1 track stubs for |η| < 1
  - **Red curve** Current (5x5 crystal) L1 calorimeter granularity
  - **Green curve** Single crystal-level position resolution
    - *Better position resolution → improved performance matching L1 e/γ object to tracker*

- Working-point corresponding to 90% signal efficiency
- Rate reduction factor **~10** **(~6)** for **single** **(5x5)** crystal granularity for $E_T > 20$ GeV

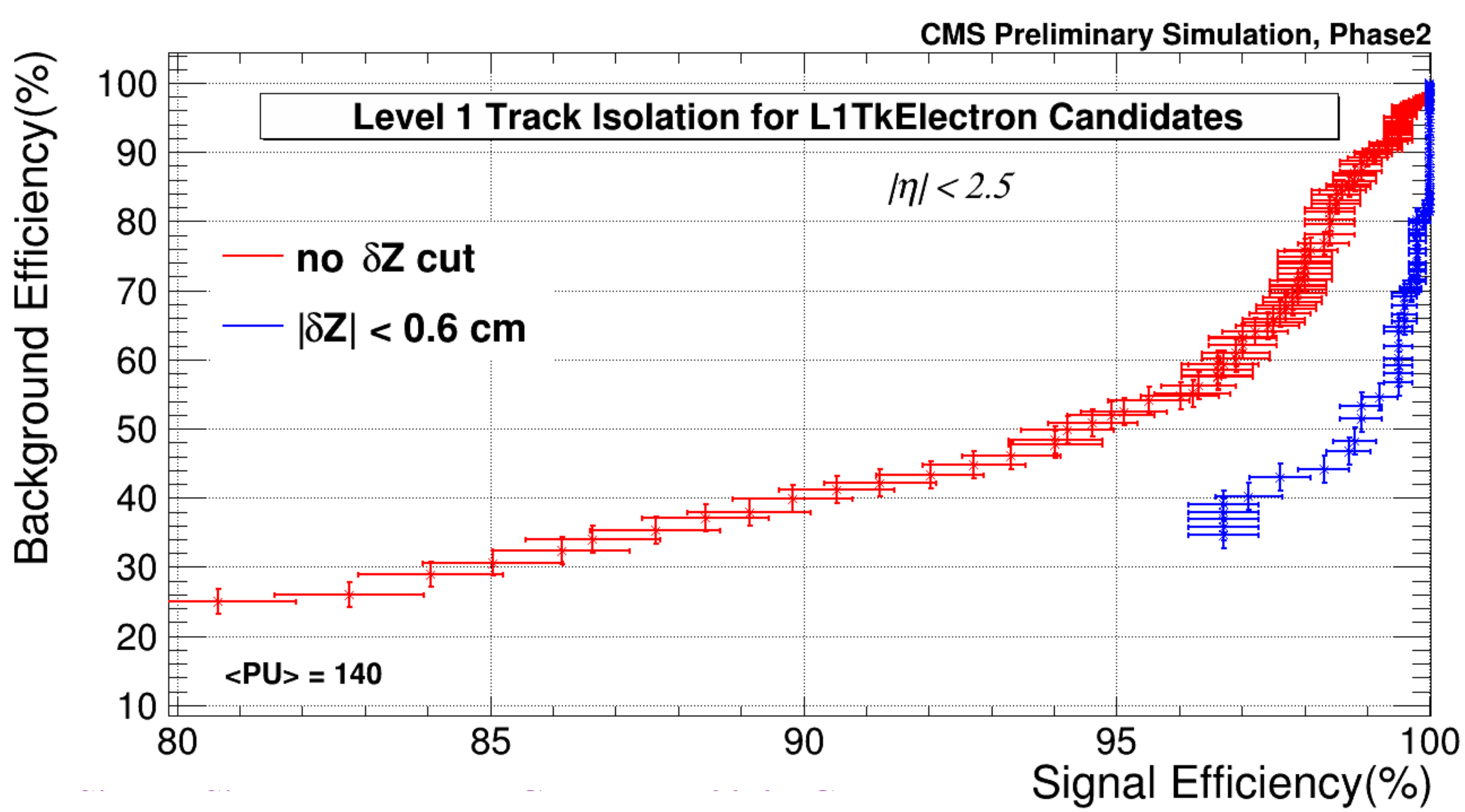


Track Isolation

- Track-based isolation for electrons
  - Define relative isolation = $\sum p_T(\text{track}) / E_T(e/\gamma)$
    - *Sum over tracks with $p_T > 2$ GeV*
    - **Without** *or* **with** *δZ cut*

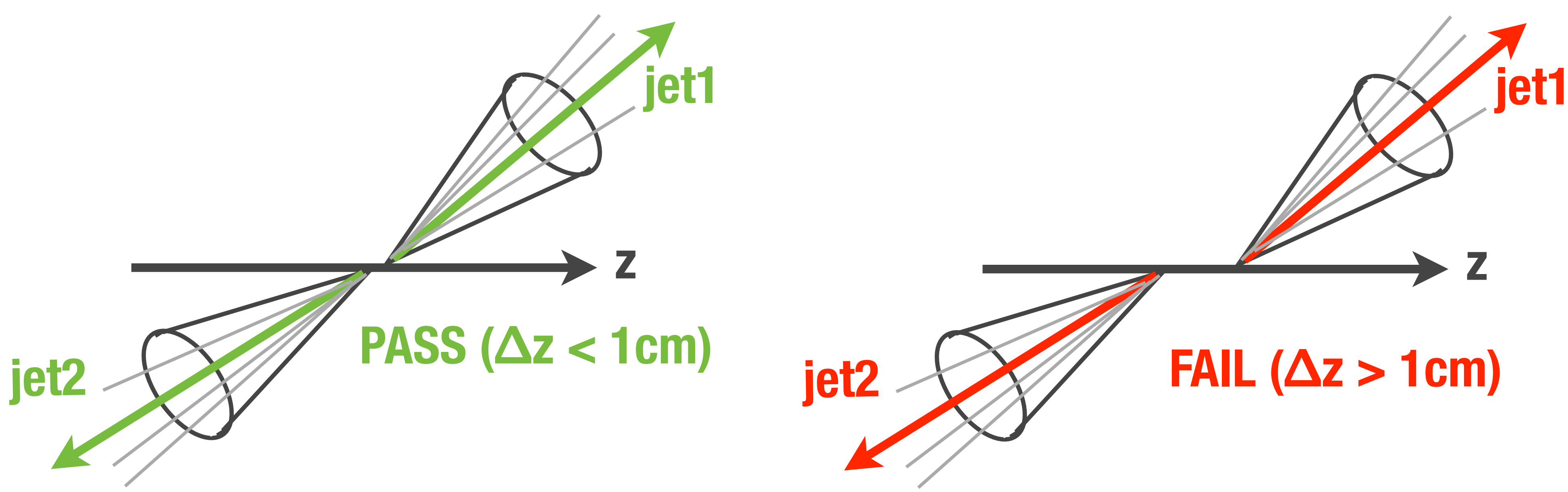


- Isolation efficiency shown for events in which a L1 track-electron candidate with $E_T > 20$ GeV was found
  - Signal is single electron events (<PU>=140) with E_T = 20-25 GeV
- Can achieve factor 2 rejection for 99% signal efficiency



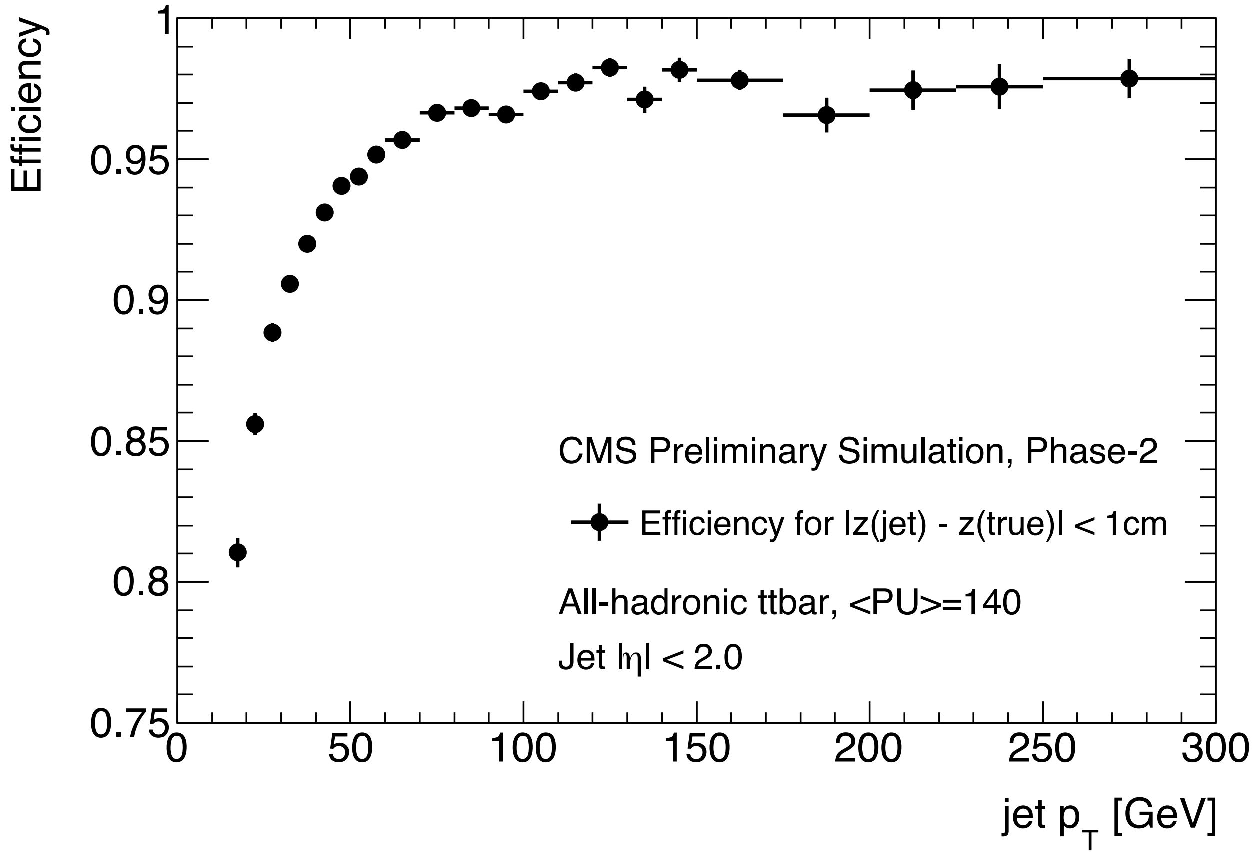
Hadronic Triggers

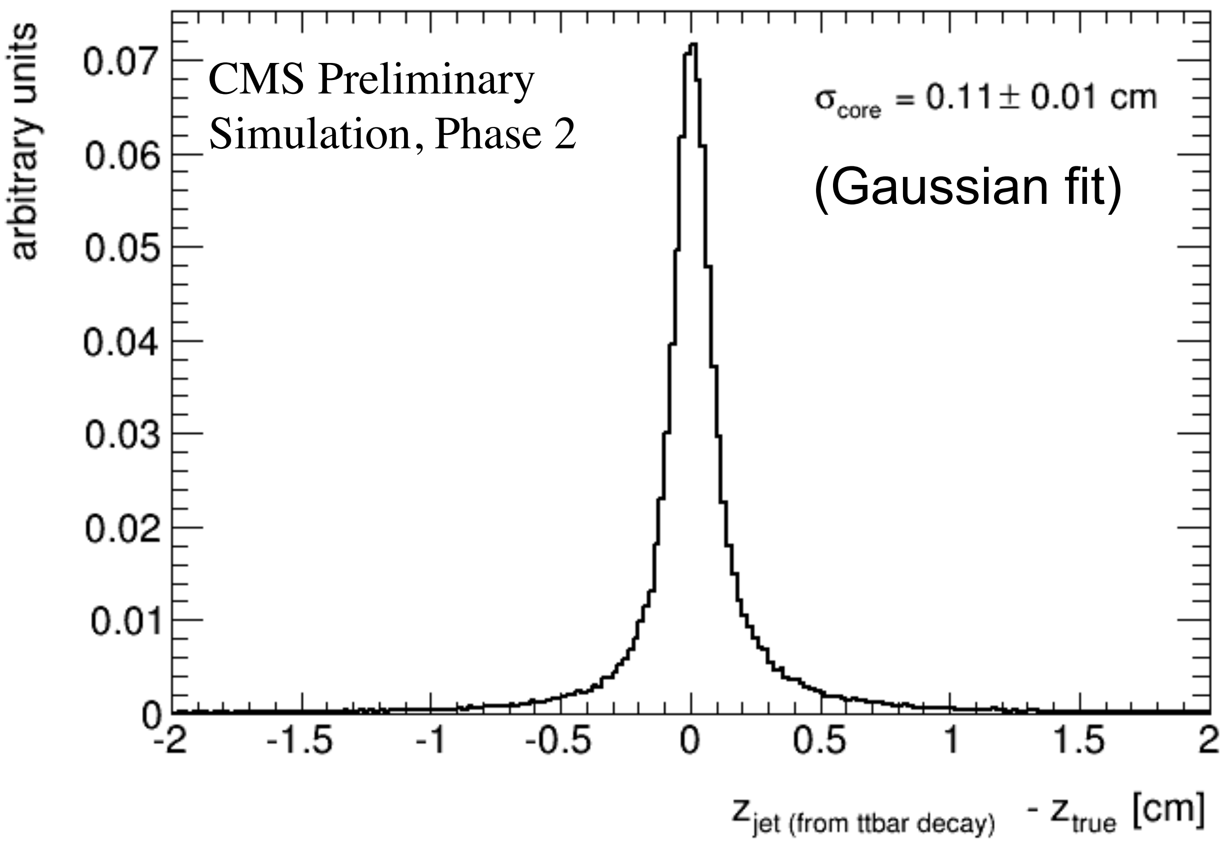
- Jet's z position measured by associating the jet to nearby L1 tracks
- Define hadronic triggers requiring vertex consistency
  - **Multijet triggers**
    - *n jets from same vertex ($|z(jet) - z_{EVT}| < 1cm$)*
  - **H_T (missing H_T) triggers**
    - *No vertex association: H_T = sum(jet p_T) for all jets ($p_T > 15$ GeV & $|\eta| < 2.0$)*
    - *Vertex association: H_T = sum(jet p_T) for jets with $|z(jet) - z_{EVT}| < 1cm$*



Jet z Position

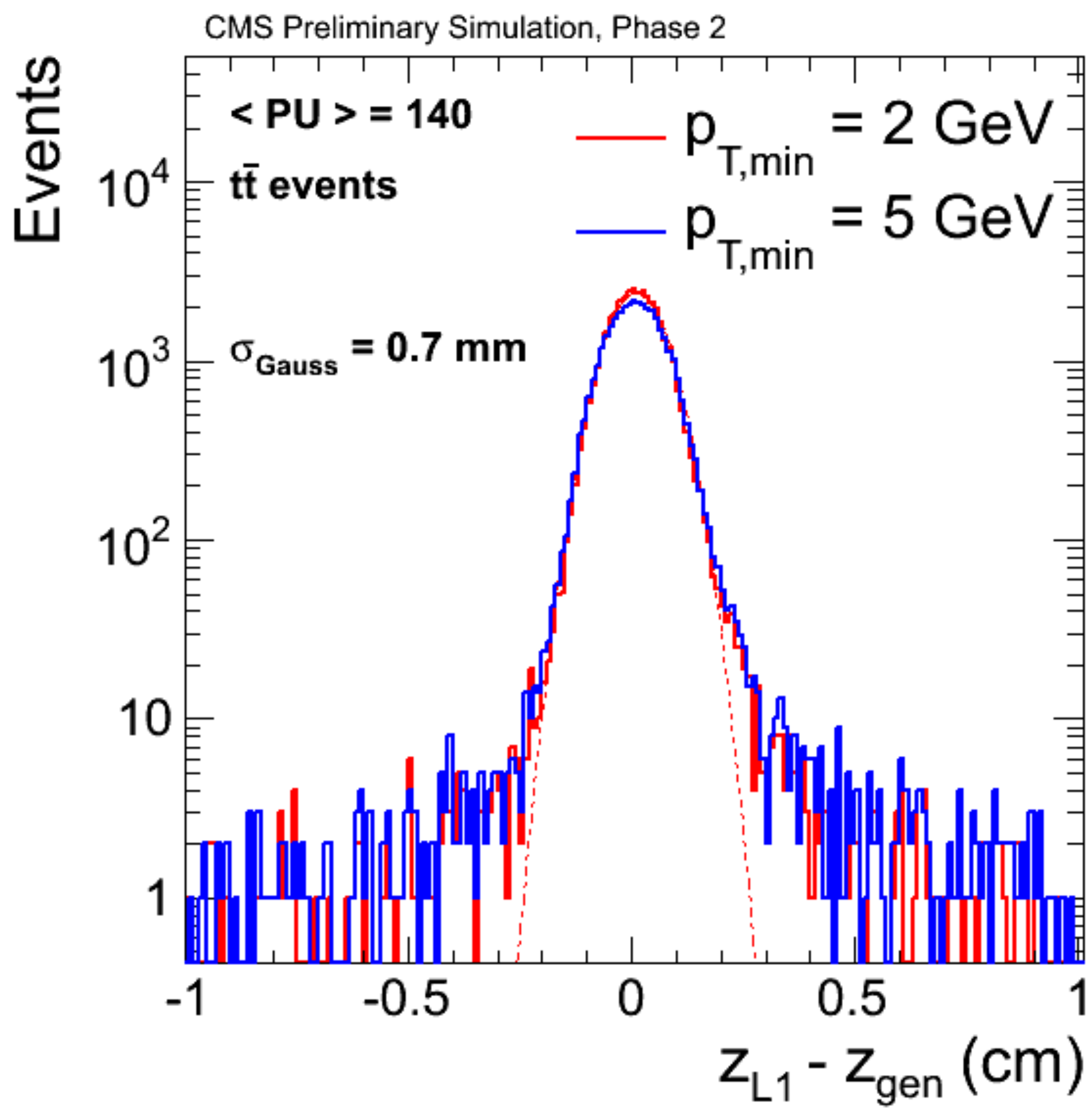
- Jet vertex performance in all-hadronic ttbar events (<PU>=140)
  - High efficiency to accurate measure z position ($|z_{jet} - z_{true}| < 1cm$)
  - ~1mm resolution (Gaussian core)





Primary Vertex & Track MET

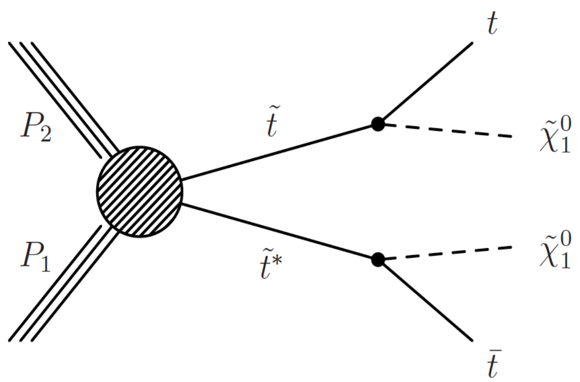
- L1 tracks can also be used to reconstruct primary vertex of event
- Resolution of primary vertex using L1 tracks with p_T > **2 GeV** or **5 GeV**
  - <1mm for events with large track multiplicity
    - *Here: ttbar <PU>=140*
  - Similar performance with the higher track p_T threshold

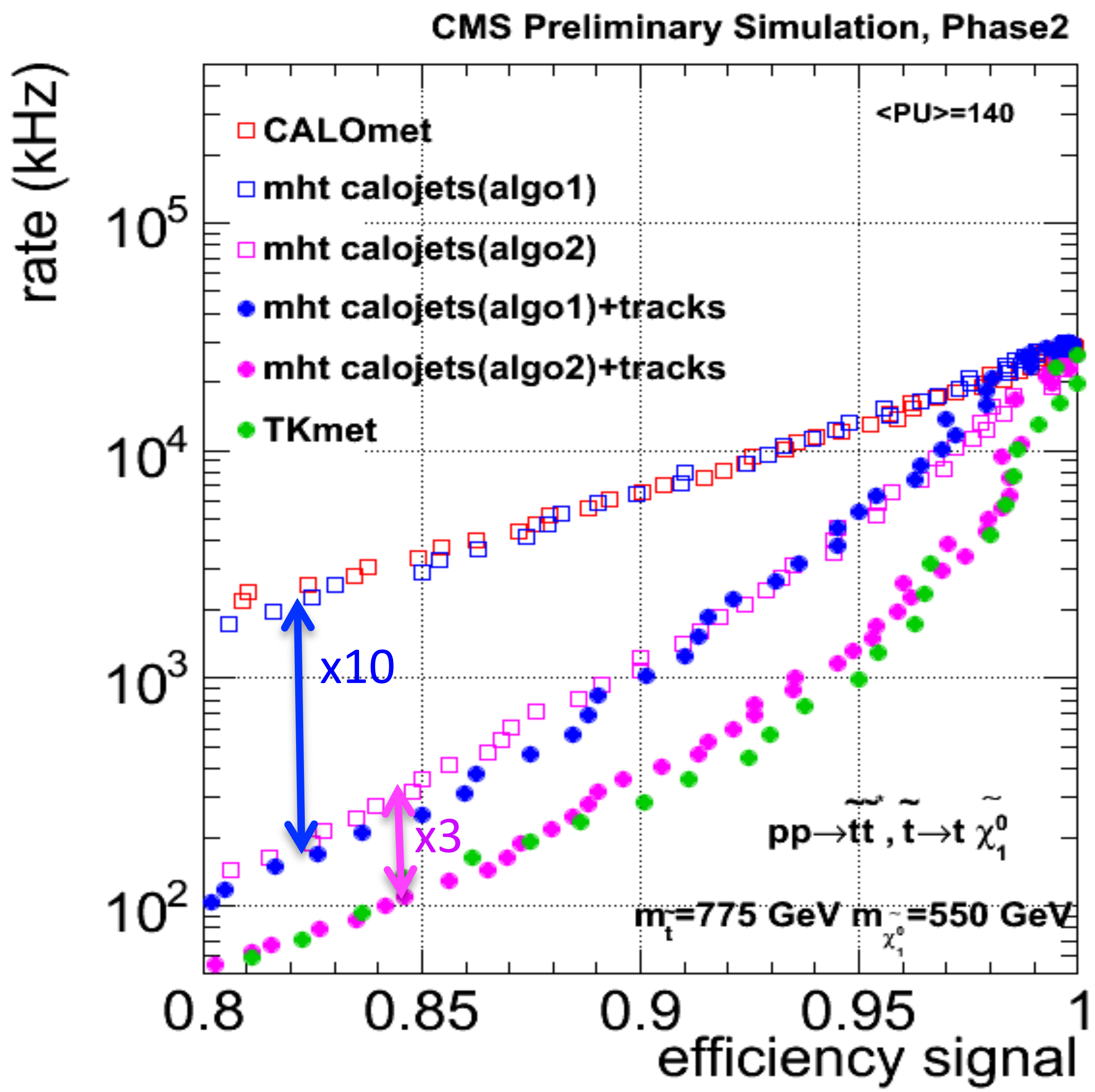


- **Track "MET"**
  - Define L1 track-based missing transverse momentum from L1 tracks coming from primary vertex

SUSY Signal Point

- Rate reductions using L1 tracks for SUSY signal
  - Stop pair production with hadronic top decays (stop=775 GeV, LSP=550 GeV)
  - Signal defined by genMET > 100 GeV





- Missing H_T determined with/without vertex association
  - Algo1 & Algo2: Calorimeter-based L1 jet algorithms with different PU subtraction methods
- Sizable rate reductions achieved with tracking information!

Conclusions

- New central tracker with triggering capabilities for CMS for phase-2 upgrade
- Tracklet-based approach to tracking at L1
  - Simulation of tracklet-based algorithm integrated to CMS software framework
  - Studies of its performance show very promising results!
    - *High efficiency & precise track parameters achieved*
    - *E.g. $\sigma(z_0)$ ~ 1mm & $\sigma(p_T)/p_T$ ~1% for wide range of η*
- Incorporating L1 track information to L1 trigger gives sizable rate reductions
  - Factor ~10 in e/μ identification
  - Factor ~2 in track isolation
  - Large rate reductions also for hadronic triggers
- Including tracking information at the L1 trigger important to achieve necessary rate reductions as driven by the physics!